A New Ultra-Cold Neutron Source for Fundamental Physics Measurements at LANSCE

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Introduction

Ultra-cold neutrons (UCNs) are neutrons of sufficiently low energy that they cannot penetrate the potential barrier formed by a variety of materials. They have a variety of characteristics that make them uniquely suitable for high-precision measurements of the properties of the decay of the neutron, which are intimately tied to fundamental physics. For example, the neutron decays, with a lifetime of about 890 s, into a proton, an electron, and a neutrino. There is an angular correlation between the direction of the spin of the decaying neutron and the angle of emission of the electron. Measurement of this correlation, called A, when combined with knowledge of the neutron lifetime, determines the values of the vector and axial vector weak coupling coefficients. We have proposed a new experiment to measure the A correlation using UCNs produced at a new source to be built at the Los Alamos Neutron Science Center (LANSCE).

Properties of Ultra-Cold Neutrons

Because UCNs lack the energy to penetrate the surface of a material, they undergo total external reflection at all angles. The probability that a UCN will be absorbed on each bounce has been measured to be very small: less than one in ten thousand. Therefore, UCNs can be stored in a bottle for long periods of time, greater than 100 s. Also, they can be guided through pipes with sharp bends. Together, these facts allow an experiment using UCNs to be shielded from the source of the neutrons both by physical shielding (because one can transport the UCNs around the shield material) and by time (because one can store the UCNs in a bottle until the background caused by the production process has died away). Also, UCNs have sufficiently low energy that they can be 100% polarized by passing them through a magnetic field of about 7 Tesla. UCNs with spins coaligned with the field pass through it, but those with spins aligned in the opposite direction are turned back by a potential higher than their kinetic energy. Therefore, 100% polarized UCNs can be available to an experiment that measures correlations to the spin of the neutron. Previous measurements of the A correlation have been dominated by the systematic errors caused by high backgrounds and incomplete polarization of the neutrons; both of these effects are almost eliminated by using UCNs for the measurement. These two factors will allow our experiment to achieve unprecedentedly low systematic errors for an A correlation measurement, and also systematic errors that are independent of those affecting the previous measurements conducted using cold neutrons or at reactors. The dominant systematic uncertainties for our experiment will be caused by depolarization of the UCNs by interactions with the walls of their decay volume and by interactions with the magnetic fields in the decay volume.

In order to run our experiment, however, we need to build a new source to supply it with UCNs. No existing source in the world can supply enough UCNs with low enough background rates for the experiment to work. In principle, UCNs could be produced in cold neutron sources by thermal processes. Energetic neutrons from a reactor or spallation source would be moderated by a material,

such as liquid hydrogen, at a temperature of about 20 K. The resulting temperature distribution of the neutrons, called the Maxwell-Boltzmann distribution, has long tails that reach to high and low energies, even down to the energy region of UCNs. But the number of UCNs produced by this method would be relatively small because the UCN energy region is orders of magnitude lower than the moderator temperature, and the number of UCNs produced would be suppressed accordingly.

Therefore, in order to produce UCNs in quantity, it is necessary to somehow enhance their production. This is possible using the super-thermal UCN production process. If the dominant interaction between the neutrons and the medium through which they pass is by single-phonon absorption or creation, then UCN production will be (possibly greatly) enhanced. A cold neutron can downscatter to produce a UCN by creating a phonon and giving up the corresponding energy. The probability of this happening is proportional to the density of states available for the phonon to be created in. Similarly, a UCN can upscatter by absorbing a single phonon and receiving its energy and turn into a cold neutron. But if the temperature of the moderator is much less than the temperature of the cold neutrons, relatively few phonons will be available for the UCN to achieve upscatter by absorption. So, the upscattering process is suppressed in such a material, which results in greatly enhanced UCN production over thermal rates. Candidate materials are rare, though. In addition to the single-phonon interaction forming a link between cold-neutron and UCN energies, the nuclear absorption in the material must be very small; otherwise, the UCN will likely be absorbed before it can escape from the medium in which it was created. Only two materials satisfy the requirements: superfluid helium and solid deuterium.

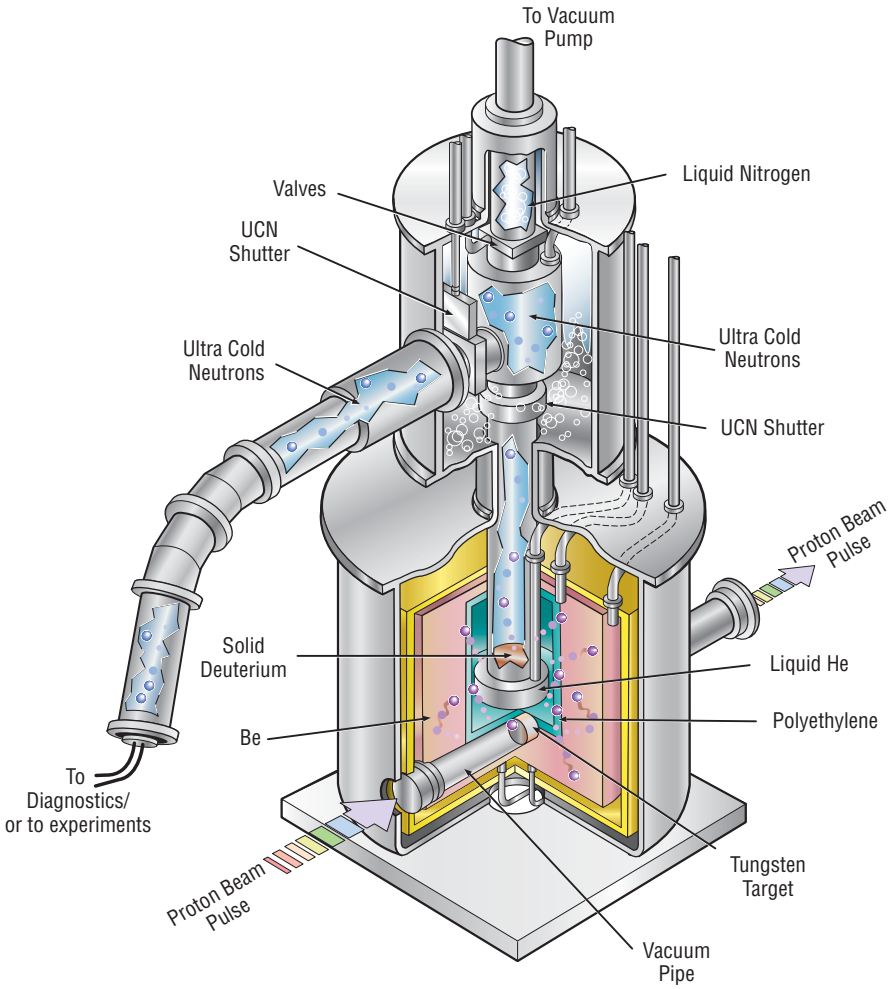

Figure 1. A concept drawing of the prototype UCN SD_2 source. The 800-MeV proton beam from the LANSCE accelerator strikes the tungsten target, producing about 18 neutrons for every incident proton. These neutrons are reduced to cold-neutron temperatures (~40 K) by scattering in polyethylene moderators at 4 K and 77 K. They downscatter into the UCN regime as they interact with the solid deuterium.

Our Approach to Enhanced Ultra-Cold Neutron Production

For the past several years, our collaboration has been working to design and build a UCN source based on enhanced production in solid deuterium. In our source, the 800 MeV proton beam at LANSCE hits a tungsten spallation target (see Figure 1). Each incident proton produces about 18 energetic neutrons in the spallation target. These neutrons are reflected by and contained in a box made of beryllium metal. Layers of polyethylene at liquid-nitrogen temperature (77 K) and liquid helium temperature (5 K) moderate the neutrons to a temperature of about 40 K. Inside the polyethylene moderators is a stainless steel pipe coated with a thin layer of nickel-58. The pipe, in turn, contains a block of solid deuterium at a temperature of about 5 K. The cold (40 K) neutrons can pass right through the stainless-steel-and-nickel wall of the pipe, but when they encounter the solid deuterium, some of them are downscattered to produce UCNs. These UCNs are now trapped in the pipe, or guide tube, because nickel-58 has a high enough potential to hold UCNs. So the UCNs, if they escape the deuterium without being absorbed or upscattered again, bounce off the interior walls of the guide tube and are conducted to a bottle, detector, or experiment away from the source. For our test setup, shown in Figure 1, we had a bottle formed of a length of guide tube with valves at both ends atop the source and a detector at the bottom of a vertical stretch of tube off to the side of the detector.

Problems in Producing Ultra-Cold Neutrons

We have tested and improved our prototype UCN source from 1998 to 2000. In the early tests, in 1998–1999, the source produced far fewer UCNs than predicted. Much of our subsequent work has focused on identifying and eliminating this unexpected suppression. The first version of the source had a cold aluminum window above the solid deuterium block, which was designed to confine the deuterium to the cold region of the guide tube. Unfortunately, it also confined the UCNs to that region. Aluminum would normally be almost transparent to UCNs, because both its potential and absorption are low, but the window in our source was opaque. Because the window was cold (about 20 K), any impurities in the deuterium gas used to fill the cell froze out on the surface of the window. These impurities, such as water, oxygen, and nitrogen, have high enough potentials and absorptions for neutrons that no UCNs could get through them.

After eliminating the window from the system, so that the UCNs had an unobstructed path from the deuterium to a storage bottle or detector, we still observed unexpectedly low UCN production from the source. It was clear that the UCNs were failing to escape from the solid deuterium block. After a UCN is created in the deuterium, by being downscattered from a cold neutron, it starts to travel through the deuterium. As it passes through the solid deuterium, it can get upscattered again by reacting with a phonon in the deuterium crystal, or it can get absorbed on either a deuterium nucleus or a hydrogen nucleus which has contaminated the deuterium. Because the cross section for each of the processes is proportional to the inverse of the velocity of the UCN, the probability of each interaction occurring and removing the UCN can be characterized by a lifetime that it is independent of UCN velocity. The lifetimes caused by each process then add like resistances to form the total lifetime for a UCN in solid deuterium. That is, if there are three limiting processes, with lifetimes designated τ_1–τ_3, then the total lifetime, τ_T, would be

$$\frac{1}{\tau_T} = \frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3}. \qquad (1)$$

The lifetime caused by nuclear absorption on deuterium (~150 ms) is unavoidable. All deuterium has some contamination of hydrogen atoms, but the lifetime caused by nuclear absorption on hydrogen can be extended by reducing the hydrogen contamination. If the hydrogen contamination is reduced to 0.2%, then the lifetime for nuclear absorption on hydrogen is also about 150 ms. Finally, the lifetime for phonon absorption from the deuterium crystal is dependent on the temperature of the deuterium, because the population of phonons increases with higher temperature. For a deuterium temperature of 5 K, the lifetime for phonon

absorption is also 150 ms. If you add these three lifetimes as resistances (using Equation 1), the total lifetime is 50 ms. Because a UCN moves at a speed of about 0.5 cm/ms, and the thickness of the solid deuterium was about 10 cm, we expected the UCN to escape from the solid in about 20 ms. As 20 ms is less than the predicted lifetime of 50 ms, we expected a substantial fraction of the UCNs would escape. But we detected dramatically fewer UCNs than we expected. We realized that we needed to directly measure the UCN lifetime in the deuterium in order to check the predicted lifetime of 50 ms.

The lifetime of the UCNs in the solid deuterium can be measured by not allowing the UCNs to travel directly along the guide tube from the deuterium to the detector, but instead of trapping them in the section of tube with the deuterium for varying lengths of time after production, then counting how many survive. UCNs trapped in the section of guide with the deuterium can be lost in three ways: first, they can be lost by interacting with the walls of the guide or with the valve trapping them with the deuterium. Second, they can be lost by interacting with the deuterium. Finally, they decay with a lifetime of about 890 s. We could disregard this last source of loss because the other two sources have much shorter lifetimes and dominated the loss. Thus, the sum (as resistances) of the wall losses and the deuterium losses formed a total lifetime of the system. We directly measured this total lifetime by counting the reduction in detected UCNs as a function of the amount of time they were trapped within the deuterium (see Figure 2). Because the lifetime caused by wall losses in the guide could be predicted both analytically and by using Monte Carlo techniques, we could then extract the lifetime of the UCNs in the deuterium.

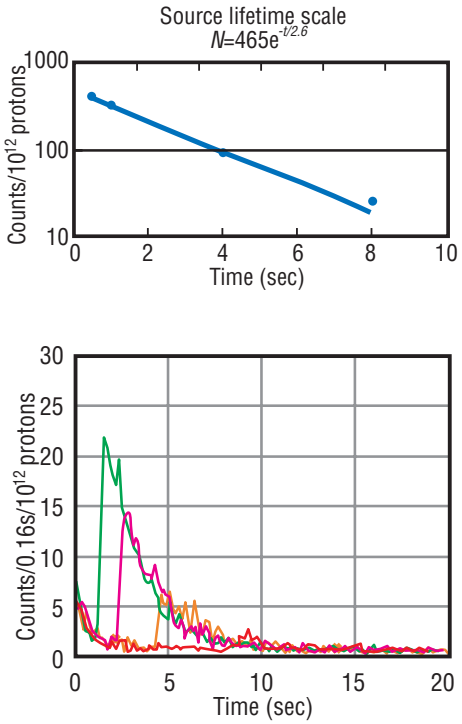

Figure 2. SD_2 Lifetime Measurements. The UCNs were trapped in a 5 L bottle that also contained the solid deuterium moderator. The exit valve was opened after different times. The detected UCNs are shown in the bottom plot for different opening times. The decrease in detected UCNs for later opening times (shown in the top plot) corresponds to the lifetime of UCNs in the system, which is 2.6 s in the example shown. By correcting for other sources of UCN loss, the lifetime of UCNs in the solid deuterium could be extracted. In the example shown, the lifetime in the SD_2 was about 30 ms.

Our Solution

The result was surprising: the lifetime was only a few milliseconds—not the 50 ms that we had predicted. Another source of loss of UCNs must exist in the deuterium in addition to the three listed above. The deuterium molecule, like the hydrogen molecule, has different spin states. In hydrogen, the spins of the two protons in the molecule can either be aligned (total spin = 1) or opposite to each other (total spin = 0). The first state is called ortho-hydrogen, and the second is called para-hydrogen. In deuterium, the situation is slightly more complicated, because deuterium has a spin of 1, as opposed to hydrogen, which has a spin of 1/2. The total spin of the two spin-1 deuterons in a deuterium molecule can be either 0, 1 or 2. The two states with even total spins are called ortho-deuterium and the state with odd total spin is called para-deuterium. Ortho-deuterium is the ground state (the state with the lowest possible energy); para-deuterium has an energy about 7 meV higher than ortho-deuterium. Because 7 meV is much greater than the typical UCN energy of 100 neV, if a UCN were to cause the transition from para- to ortho-deuterium to occur and receive some of the released energy, it would definitely be upscattered and no longer be a UCN. At room-temperature equilibrium, 33% of deuterium is in the para- state, so there are plenty of para-deuterium molecules available to give up their 7 meV of energy to passing UCNs.

Members of our collaboration made the first calculation of the upscattering probability for UCNs on para-deuterium and found that the cross section is large enough that the room temperature abundance of para-deuterium was sufficient to explain the very short lifetimes we had observed. But they found that if the fraction of para-deuterium could be reduced to about 2%, the lifetime caused by this new upscattering process would be about 150 ms, comparable to the lifetimes caused by the other sources of UCN loss. The total lifetime for a UCN in the deuterium would then be predicted to be about 38 ms. Because we needed to increase the lifetime of the UCNs in the solid deuterium in order to increase the number of UCNs produced by the source, we built a converter to change the para-deuterium to ortho-deuterium before it was introduced into the guide tube. The converter consisted of a cell full of a material, ferrous hydroxide, which has both a magnetic moment and a large surface area. By exposing the deuterium to this material, held at a temperature of about 20 K by the cold head of a cryo-pump, we can reduce the fraction of para-deuterium to below 2%.

Experimental Results

When we measured the lifetime of the UCNs in the deuterium using the converted deuterium, we saw the expected value. Furthermore, the lifetime depended on the para-deuterium fraction and the temperature of the solid deuterium in the predicted way. Finally, the number of detected UCNs was greatly enhanced relative to our earlier measurements and was close to our Monte Carlo predictions of UCN production. This higher UCN production encouraged us to test our prototype source at proton currents comparable to those to be used for a full-scale production UCN source. The result of the test was the highest density of UCNs stored in a bottle in the world so far (see Figure 3). The linearity of the number of detected neutrons with incident proton charge was also encouraging because it indicates that the full-scale source would not be limited by beam heating or other effects of higher proton currents.

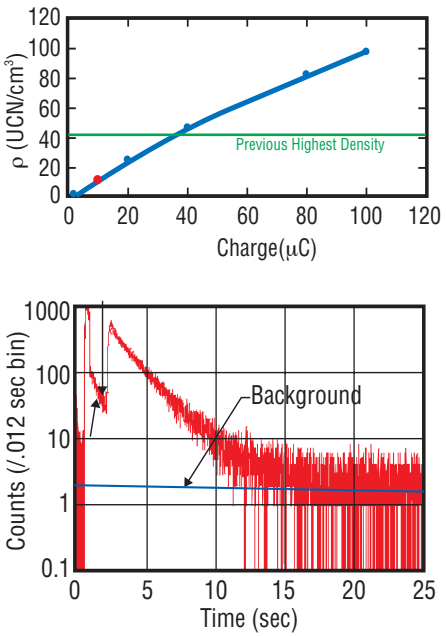

Figure 3. World Record UCN Density. On June 29, 2000, we tested the prototype UCN source with beam intensities similar to those we would use for the full-scale source. The result was the highest density ever achieved of UCNs stored in a bottle, a factor of 2.5 greater than the world's previous highest density. The top plot shows the density achieved as a function of incident proton charge. The bottom plot shows the time structure of the detected UCNs, after the start of the proton pulse at time zero. The UCNs were stored for 1/2 second, from t = 2.0 to t = 2.5 s. About 30,000 UCNs were detected in the run shown, which corresponded to an incident charge of 100 microCoulombs of protons and a UCN density of 100 UCN/cc.

Summary and Outlook

We are therefore proceeding to design and build a full-scale UCN source to be installed at LANSCE. Our predictions are that steady state UCN densities of about 300 stored UCN/cm^3 will be achieved, as opposed to the 10 UCN/cm^3 we stored in our test run and the 41 UCN/cm^3 that had previously been achieved by a production source. A density of 300 UCN/cm^3 will allow us to make measurements with previously unattainable precision of neutron decay asymmetries, and hence of the weak coupling constants. The first experiment, by making precise measurements of the weak coupling constants, will push the limits of our understanding of the fundamental forces of nature, and possibly even prove that the standard model, which describes the fundamental particles, is incomplete. The design and initial stages of construction of the full-scale source and first experiment are now in progress. Possible upgrades to the first source are now being studied, as well: UCN densities of up to several thousand per cubic centimeter might be possible with an upgraded source. Such a source could supply UCNs to a user facility, supporting multiple experiments running at the same time. These experiments could simultaneously make the world's best measurements of the neutron lifetime, electric dipole moment, and decay constants, for example. The first source and experiment, while making the best measurement so far of the A decay constant and testing the standard model, will also prove the feasibility of such a source and user facility, which could be completed and on line within ten years. The development of the UCN source at LANSCE achieved a density of 100 UCN/cm^3 (2.5 times the previous world record) in its first two years of work; in the next year, the full-scale source will achieve another factor of three increase in density, to 300 UCN/cm^3; and we hope that our work over the next several years will raise the best density by up to another factor of a 30, to several thousand UCN/cm^3. A new era of precision UCN-based measurements is starting, and Physics Division and Los Alamos are in the lead!

For Further Reading

R. Golub, D. Richardson, and S. Lamoreaux, *Ultra-Cold Neutrons*, (Adam Hilger, Bristol, 1991).

C. Y. Liu, A. R. Young, and S. K. Lamoreaux. "Ultracold Neutron Upscattering Rates in a Molecular Deuterium Crystal," *Physical Review B* 62, 2000. p. 3581.